Multiasteroid Comet Missions Using Solar Electric Propulsion

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Theme

COMETS and asteroids are objects of growing scientific interest because they are likely to yield information on the early history of the solar system. To obtain a clear understanding of these bodies, several will have to be studied at close range. This can be done most economically if a spacecraft encounters several bodies in succession on a single trajectory. Techniques for the generation of such trajectories that are suitable for solar electric propulsion and sample results are the subject of this Synoptic.

This work does not attempt to justify the SEP mission mode or the particular targets used in the examples as being programatically attractive. Specifically, there is no discussion of the relative merits of SEP and ballistic flights from cost, practicality, performance or other standpoints. On the other hand, one programmatically significant conclusion was found: any SEP mission which traverses the asteroid belt should be considered a potential multicomet-multiasteroid mission, and the techniques presented in this synoptic can be applied to find opportunities for encounters.

Contents

Two rather distinct methods can be used to generate multibody low-thrust trajectories. In method 1, a specific target is selected and an initial trajectory designed without regard to additional encounters but which takes the spacecraft through the asteroid belt. Close approaches of asteroids and comets to the trajectory are determined and the trajectory modified so as to encounter one or more of them at very close range en route

In method 2, an arbitrary but reasonable trajectory (or series of trajectories) that enters the asteroid belt is adopted. Searches are made for asteroids or comets that happen to come close to the trajectory. A close approach is selected and the trajectory modified so that the encounter is at very close range. The modified trajectory may then be propagated ballistically beyond the encounter and searched for later approaches. The encounter distance used in either method for this preliminary study is set at zero, but the actual distance used in a mission will depend on the navigation and science requirements.

Both these methods have been used previously to study multibody mission using impulsive ΔV. Brooks,[1] for instance, has shown that multiasteroid flyby opportunities are very numerous and require only a modest velocity expenditure (a few hundred m/sec).

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This Synoptic exercises both methods using solar electric propulsion. For method 1, six examples were studied using the comets P/Encke and P/Kopff and the asteroid 20/Massalia as principal targets. For each target both rendezvous and flyby missions were considered. On each of these flights, encounters of one or more asteroids can be found between launch and final target encounter.

The asteroids and comets considered as possible targets include the asteroids in the 1972 Russian Ephemeris,[2] 57 periodic comets of more than one appearance,[3] the Palomar-Leiden asteroids of quality 3 or better,[4] and several recently discovered asteroids whose orbits have been calculated. For example, using the 720-day flight to flyby P/Encke at 6 km/sec in 1980, there were found 18 asteroids and no comets that would approach the initial trajectory within 25 million km. Asteroids that happen to pass within about 15 million km of the nominal trajectory can be considered as possible intermediate targets since the path can be varied slightly with only a small degradation to performance. The interval between successive flybys will generally have to be of the order of 200 days to allow time for the trajectory modification. Thus on flights of less than 2 yr to a specific target, two asteroid flybys are not likely to be feasible.

One technique for generating a series of trajectories sweeps the launch date over a period of several years. About 50 opportunities per year can be found out to about 1.9 a.u. for the first encounter. One of these is selected and a solar electric trajectory to fly by it at a reasonable speed is generated. Further encounters for this case or for the case of a flyby of a specific target are found as described above (method 2). If the trajectory lies in the denser region of the asteroid belt, frequent approaches will be found in the range 0 to 15×10^6 km, sometimes as many as three every 100 days. On the other hand, if it dips inside about 2 a.u., there can be long intervals during which no such approaches are found.

The low-thrust trajectories studied and presented in this report have been obtained with Chebytop.[5] Since Chebytop optimizes only one leg of a trajectory at a time, a modification of it was developed by C. G. Sauer[6] for the purpose of optimizing the payload on a two-leg trajectory constrained to fly by an intermediate object in a given orbit. The problem of optimizing a two-asteroid flyby enroute to a given target was solved approximately by an iterative sequence using Sauer's version of Chebytop on the first two legs and on the last two legs alternately. The results presented are thus only partially optimized but the authors feel that they are sufficiently accurate to be used as an indication of mission feasibility.

The missions studied include two four-asteroid sequences for 1975 launches found by method 2 with net masses determined for an Atlas/Centaur/5-kw SEP spacecraft, and the six missions to Encke, Kopff, and Massalia mentioned above with net masses determined for a Titan IIIE/Centaur/15-kw SEP spacecraft. Housekeeping power allowances of 200 w and 600 w, respectively, were allowed for the two spacecraft. In Table 1, a summary of these eight missions is presented along with a partial list of the asteroid encounters that were found.

The feasibility or nonfeasibility of a mission for the spacecraft suggested is indicated by the total mass delivered to the final target. For example, since current estimates for solar electric propulsion systems indicate a specific mass of about

Table 1 **Summary of missions studied**

Launch date mission (encounter relative to perihelion)	Total flight time, days	Target list	Total spacecraft mass (at last target), kg
Feb. 3, 1975, four-asteroid flyby[a]	1150	1204, 1188, 63, 1378	719
March 15, 1975, four-asteroid flyby[a]	1250	33, 1720, 192, 1419	681
March 7, 1978, Encke rendezvous[b] (T_p-45 days)	960	Direct to Encke 214, Encke 465, Encke 214, 465, Encke[c]	1063 1058 1019 998
Oct. 28, 1978, Encke flyby[b] ($V = 6$ km/s on T_p-50 days)	720	Direct to Encke 1601 1601, 787, Encke	1354 1300 1284
April 30, 1981, Kopff rendezvous[b] (T_p-50 days)	790	Direct to Kopff 8, Kopff	812 795
April 30, 1981, Kopff slow flyby[b] ($V = 2$ km/sec on T_p-50 days)	790	Direct to Kopff 8, Kopff 8, 2530PL, Kopff	1492 1460 1357
June 6, 1982, Massalia rendezvous[b]	600 600 600	Direct to 20 207, 20 207, 435, 20	1278 1254 699
June 6, 1981, Massalia flyby[b] ($V = 1$ km/sec) and beyond	600 1030	Direct to 20 207, 20, 824, 1675	1794 1720

[a] Atlas/Centaur/5-kw SEP.
[b] Titan IIIE/Centaur/15-kw SEP.
[c] Illustrated in Fig. 1.

30 kg/kw it appears that the Titan IIIE/Centaur/15-kw SEP spacecraft is inadequate for the Kopff rendezvous missions and for the Massalia two-asteroid flyby-to-rendezvous mission. Similarly this spacecraft would be more than adequate for the Kopff flyby mission studied and the mission could be modified to use a shorter flight time or a slower flyby velocity if it is desired to redesign to this vehicle.

In Fig. 1 there is shown a two-asteroid flyby trajectory for the 1980 Encke rendezvous mission. It is an ecliptic plane projection showing the spacecraft trajectory with thrust vectors and the orbits of the targets with dates of encounter.

The pertinent conclusions from this analysis are these: 1) Flights passing through the asteroid belt can be modified with SEP to pass by one or more asteroids enroute. 2) The performance penalty for intermediate asteroid encounters is generally small if the encounters are properly spaced. 3) A vehicle in an asteroidlike orbit (as results from a slow flyby of a main belt asteroid) can encounter additional bodies for very little fuel to the lifetime limit of the spacecraft. 4) Although all the implications on the spacecraft and navigation systems have not been treated here, it appears that the requirements are no more (or less) stringent than for similar single-body missions. Finally it is the opinion of the authors that any SEP flight under serious consideration that passes through or near the asteroid belt is a potential multicomet-multiasteroid mission and should be examined accordingly.

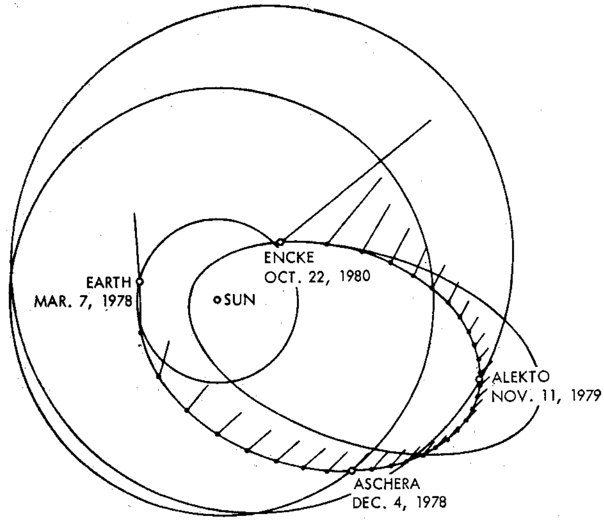

Fig. 1 SEP Encke rendezvous with flybys of 214/Aschera and 465/Alekto.

References

[1] Brooks, D. R. and Hampshire, W. F., II, "Multiple Asteroid Flyby Missions," 12th Colloquium of the International Astronomical Union, Tucson, Ariz., March 8–10, 1971; also in *Physical Studies of Minor Planets*, edited by T. Gehrels, SP-267, 1971, NASA.

[2] *Ephemerides of Minor Planets for 1972*, U.S.S.R. Academy of Sciences, Leningrad, 1971, pp. 12–44.

[3] Porter, J. G., "Supplementary Catalogue of Cometary Orbits (1965)," *Memoires British Astronautical Association*, Vol. 40, No. 2, July 1966, p. 16

[4] Van Houten, C. J., Van Houten-Groeneveld, I., Herget, P., and Gehrels, T., "The Palomar-Leiden Survey of Faint Minor Planets, 1970," *Astronautics and Astrophysics, Supplementary Series*, Vol. 2, 1970, pp. 339–448.

[5] Johnson, F. T., "Approximate Finite-Thrust Trajectory Optimization," *AIAA Journal*, Vol. 7, No. 6, June 1969, pp. 993–997.

[6] Sauer, C. G., "Optimization of Multiple Target Electric Propulsion Trajectories," AIAA Paper 73-205, Washington D.C., 1973.